

A Candidate Protoplanet in the Taurus Star Forming Region

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ABSTRACT

HST/NICMOS images of the class I protostar TMR-1 (IRAS04361+2547) reveal a faint companion with $10.0'' = 1400$ AU projected separation. The central protostar is itself resolved as a close binary with $0.31'' = 42$ AU separation, surrounded by circumstellar reflection nebulosity. A long narrow filament seems to connect the protobinary to the faint companion TMR-1C, suggesting a physical association. If the sources are physically related then we hypothesize that TMR-1C has been ejected by the protobinary. If TMR-1C has the same age and distance as the protobinary then current models indicate its flux is consistent with a young giant planet of several Jovian masses.

Subject headings: binaries; general — circumstellar matter — infrared: stars — planetary systems — stars: individual (TMR-1) — stars: formation

I protostars are surrounded by opaque envelopes of infalling gas and dust. Based on statistical and theoretical arguments typical ages of class I protostars are 100,000 to 300,000 years (Terebey et al. 1984; Shu, Adams, & Lizano 1987). NIR imaging and millimeter interferometry data of TMR-1 show a bipolar outflow which extends SE to NW (Terebey et al. 1990; Hogerheijde et al. 1998). Based on the arguments given in Chandler et al. (1996) TMR-1 is not viewed edge-on or pole-on, but at an intermediate ($\sim 60^\circ$) inclination.

3. HST NICMOS Images and Photometry

The high spatial resolution ($0.15''$ at $1.6 \mu\text{m}$) HST/NICMOS images in Figure 1 resolve the TMR-1 protostar into two point sources which we call A and B. A is the northern component. At the Taurus cloud distance of 140 pc the $0.31''$ projected separation is 42 AU, a fairly typical binary separation. The new data reveal TMR-1 to be a protobinary surrounded by gas and dust, viewed during the epoch of formation.

Figure 1 displays extensive nebulosity, brightest near the protobinary. A long narrow filament extends in a gentle curve from near the protobinary to a third fainter point source, which we call C, located $10.0''$ southeast. The image provides strong visual evidence that object C appears associated with the protobinary by means of the filament. TMR-1C is detected at $S/N = 50$ in the F205W filter, as implied by the presence of the Airy diffraction ring.

The image artefacts (Casertano 1997) are easily identified in the original image orientation (+y axis at P.A. = 38° E of N). Artefacts arising from the bright protostars include: the $\pm 45^\circ$ telescope diffraction spikes; electronic ghost stars at ± 128 pixels along the x,y axes; and two faint electronic ghost columns, one of which passes through the protostars, and another seen 128 pixels to the left. Finally, a residual coronagraphic spot

fewer than expected background stars because of high extinction local to the protostars. Comparable S/N HST/NICMOS images for nine class I protostars in Taurus show one other secondary object ($K = 18.7$ mag), giving one or two possible background objects in nine fields. To match the large scale NIR star counts implies an average extinction over the $20''$ NICMOS field of view of $A_K = 1$ to 2 ($A_V = 10$ to 20) towards Class I protostars in Taurus.

An alternate estimate for the extinction is set by values previously derived for the protostar, which range from 2.5 to 4 at K (Terebey et al. 1990; Whitney et al. 1997). The extinction is likely smaller at $10''$ distance from the protostar, as is also suggested by the Table 1 flux ratios. Intrinsic NIR stellar colors are near zero because the spectral energy distribution of many stars is near the Rayleigh-Jeans limit. The observed highly reddened colors of protostars are therefore caused by extinction and scattering. The increasing flux ratio of object C to either protostar between 1.6 and $2.05 \mu\text{m}$ suggests less extinction toward object C than toward A and B.

5. Luminosity and Temperature

Models of giant planet and brown dwarfs imply they are hottest and brightest when young, as luminous as $0.01 L_{\odot}$ at one million years (Nelson, Rappaport, & Joss 1993; Burrows et al. 1997). The radii are near that of Jupiter's, $R_J = 7.1 \times 10^9$ cm, over a large mass and temperature range; young objects should be modestly (up to factor of three) larger. Models suggest effective temperatures as great as 3000 K below one million years age.

The object TMR-1C is clearly much fainter than the neighboring protostars; if located at the same distance as the Taurus cloud then the estimated bolometric luminosity is

has the same 300,000 year age assumed for the protostars then A_V is 8 - 20 and the mass is 2 - 5 M_J . If the age is ten million years, the same as older pre-main sequence stars in Taurus, the mass may be as high as 15 M_J . However, below one million years the models are sensitive to the initial conditions, as the thermal relaxation timescale is comparable to the planet's age. More realistic models will depend on the planetary formation mechanism.

7. Ejection Hypothesis

If TMR-1C is a physical companion of the TMR-1 binary then models suggest it formed much closer to the protostars than its observed 1400 AU projected distance. We hypothesize TMR-1C has been ejected by the two protostars. Apart from some exceptions such as hierarchical systems, celestial dynamics finds that 3-body stellar systems with comparable separations are unstable and tend to eject the lowest mass object (Monaghan 1976). On dimensional grounds the characteristic velocity of ejection is $(GM/R)^{0.5}(1+e)$, the velocity of periastron passage of the binary. Numerical studies show a large dispersion in ejection velocities (Standish 1972).

The separation of the protostars allows us to estimate a characteristic ejection velocity. The computation is only indicative given that the orbital parameters and inclination are poorly known. The observed projected separation of stars A and B is 42 AU; statistically binaries spend most time at the widest separations. For a typical binary eccentricity of $e = 0.5$ the separation varies by a factor of three. Including a modest deprojection correction, periastron passage may occur at 15 - 30 AU separation. The corresponding ejection velocity is 5 - 10 km s^{-1} for 1 M_\odot assumed total mass. The current distance of 10'' then implies the time since ejection is about 1000 yr.

Consider for the moment that the filament marks the trail of object C. The filament's

9. Isolated Planets

We have proposed that TMR-1C is a substellar object which has been ejected by a binary protostar. There are two key experiments to test the idea that TMR-1C is an ejected protoplanet. Spectra will measure the extinction and effective temperature to better discriminate between stellar, brown dwarf, or planet origin. In several years proper motion measurements will detect TMR-1C's motion on the sky. The predicted direction may be along, or in the case of a tidal tail, at an angle to the filament (Lin et al 1998).

We outline one of the many possible mechanisms for planet ejection. Three-body numerical simulations suggest stable planetary orbits exist at radii approaching half the binary periastron separation (Benest 1996). In other words there is a maximum stable radius for planet formation in a binary system. A substellar object that migrates or forms in the zone of marginal stability is subject to orbital resonance pumping. After repeated periastron passages the object gains sufficient energy to escape the system. This mechanism does not require a gaseous disk per se, and so may apply to pre-main sequence stars as well as protostars.

The discovery of an ejected protoplanet is unexpected. However, given the prevalence of binary systems the process seems inevitable, and the question becomes how often. The idea that young planets should occasionally be ejected from their solar systems is rich in implications, both for our understanding of how planetary systems form, and in strategies for detecting isolated planets using current technology.

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Fig. 1.— True-color NICMOS HST image of protostar TMR-1 with $3'' = 420$ AU scale. There is a long narrow filament extending from the protobinary to a faint point source which is the candidate protoplanet. The inset shows a magnified view ($0.3''$ scale) of the protobinary in the central region, complete with first Airy diffraction ring around each component. The field is suffused by bright nebulosity. The region is heavily reddened, but short wavelengths have been boosted to make the nebulosity appear white. Red ($2.05\ \mu\text{m} = \text{F205W filter}$); green ($1.87\ \mu\text{m} = \text{F187W filter}$); blue ($1.60\ \mu\text{m} = \text{F160W filter}$); North is up. Display uses log stretch.

Table 2. Flux of TMR-1C^a.

R	J	F160W	F187W	F205W	K	L	Units
..	..	16.	33.	39.	μ Jy
> 22.2 ^b	> 21.2 ^c	19.6	18.5	18.2	17.9 ^c	> 13.2 ^c	mag

^aNICMOS magnitudes are based on standard 0.5'' apertures and the HST Vega system. Background structure dominates the 10% photometric uncertainty.

^b 5 σ limit from Jarrett et al. 1994.

^cApril 1998 IRTF NSFCAM data. K band has 20% photometric uncertainty; 3 σ limits elsewhere.